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USING A NIKE-AJAX MOUNT FOR OPTICAL TRACKER APPLICATIONS

by

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ABSTRACT

A procedure followed in modifying a NIKE-AJAX mount for use with an optical tracking system is presented in this report. Some aspects of the required cleanup and servicing procedure are covered, and a discussion of the complete control system design is included. Tracking errors, resulting from the servo design and mount nonlinearities, are discussed both in reference to the design, as well as in reference to the results of actual tests. An attempt has been made to keep the discussion as general as possible in order to allow maximum future use of the information obtained from this modification.

CONTENTS

ILLUSTRATIONS

Section I. INTRODUCTION

For most tracking applications, either optical or otherwise, a mount is needed to position the tracking device. The mount is normally used as a component of an automatic tracking system. One such application for the NIKE-AJAX mount is the Optical Frequency Radar for which the modification and design discussed here were performed.

The mount used for this particular application had been out of service and in need of repair for some time before it was chosen to be incorporated into a tracker. Several changes were necessary to allow tracking accuracies of 1 milliradian or less. In addition, maintenance on the mechanical parts of the mount was necessary to obtain maximum performance.

For most tracker applications, the mount would probably be operated from a remote location. In order to operate the mount from a remote location, appropriate safety features must be included in the servo and control system design.

Section II. GENERAL DISCUSSION

It is necessary to become completely familiar with every unit of a system in order to successfully complete a desired modification. To understand the operation of old equipment where little published material is available, it is often necessary to test each unit to determine its transfer characteristics. Enough tests must be completed to compare present performance with the desired performance of components of the system.

In some instances, the desired performance is not known completely; or, as in the case discussed in this report, the general specification, such as maximum required angular rate and maximum tracking accuracy, is given, but the transfer function of the basic mount is unknown. In such a situation, it is not known whether the mount can be compensated to meet the performance specification. The mathematical model must then be obtained before proceeding further. This, in theory at least, is simple. The transfer function of the separate blocks might be found in a handbook and the overall transfer function found by cascading the separate blocks. A procedure such as this might result in a transfer function with the same form as the actual system, but the several constants necessary to accomplish a successful design are difficult, if not impossible, to obtain from theory and a handbook alone. From a practical standpoint, the approach most often used to obtain a mathematical model of a system is the frequency response method. This is done by inserting an input of known frequency and amplitude into the system to be tested. The output amplitude and phase are then compared with the input, and a Bode plot is made. From the Bode plot an approximate transfer function is written by knowing Laplace transforms and the slope and phase shift contribution of each typical term. One check as to the accuracy of this first approximation is to compare its amplitude and phase plot with those obtained from the actual system. A further helpful check is to program the approximate transfer function on an analog computer and to compare its step response with the actual system step response. If both the frequency response and step response for the theoretical and actual systems compare favorably, then a high degree of confidence may be placed in the proposed transfer function.

In many cases, the first approximate transfer function is not close enough for design purposes. The analog simulation may be used to aid the determination of a more exact transfer function. By varying the gains and breakpoints of the numerator and denominator terms, a "best match" may be obtained for the actual step response.

The transfer function is then written for the modified simulation, and a new frequency response is plotted for this theoretical transfer function. In most cases, the frequency response will agree if the step response is in close agreement. It is not necessarily true that the step response will match if the two frequency responses agree.

Section III. PHYSICAL PROBLEMS

Small physical problems often cause trouble with the actual determination of the frequency response. One such problem to be considered is the determination of the open loop transfer function. In many cases, the open loop transfer function has one or more free poles at the origin. If two or more free poles are present at the origin, the frequency response data should be taken for the closed loop system and converted, by use of a Nichol's chart or other suitable means, to open loop form. Inaccuracies are always introduced when such conversions are made but, in many cases, this is the only means of obtaining open loop data. Whenever possible, it is better to measure open loop data directly.

Some of the unexpected problems which were encountered on the actual mount, before satisfactory frequency response data could be obtained, involved modification and checkout of the mechanical, as well as the electrical components. A brief discussion of some of these problems is contained in the Appendix.

Section IV. SYSTEM TRANSFER FUNCTION

After the system had been placed in good operating condition, the data for the preliminary frequency response of each unit of the system were taken.

Figure 1 shows the amplitude response for the angle modulator alone. The amplitude response for the preamplifier is shown in Figure 2, although the open loop is not used for the preamplifier and power amplifier.

Linearity checks were also made on the major components of the control loop. Output versus input plots were made for the angle modulator and preamplifier. Figures 3 and 4 show the linearity plots for the angle modulator and preamplifier, respectively. The information from these figures was used to ensure the linear operation of each component.

With the system operating linearly and as near peak performance as possible, amplitude and phase measurements for the Bode plot were taken for both the azimuth and elevation axes. Data for the azimuth axis Bode plot are plotted in Figure 5, and similar data for the elevation axis are shown in Figure 6. From these plots approximate transfer functions were chosen. These are given as:

1) First guess azimuth axis transfer function

$$G_{(S)} = \frac{0.707}{S\left(\frac{S}{2} + 1\right)\left(\frac{S}{20} + 1\right)}.$$

2) First guess elevation axis transfer function

$$G_{(S)} = \frac{0.32}{S\left(\frac{S}{8} + 1\right)\left(\frac{S}{60} + 1\right)}$$

In order to check the approximate transfer functions, theoretical Bode plots were made for the chosen transfer functions. Although these plots were not identical, the differences indicated that a "good match" was found with the first guess transfer functions. As discussed earlier, a

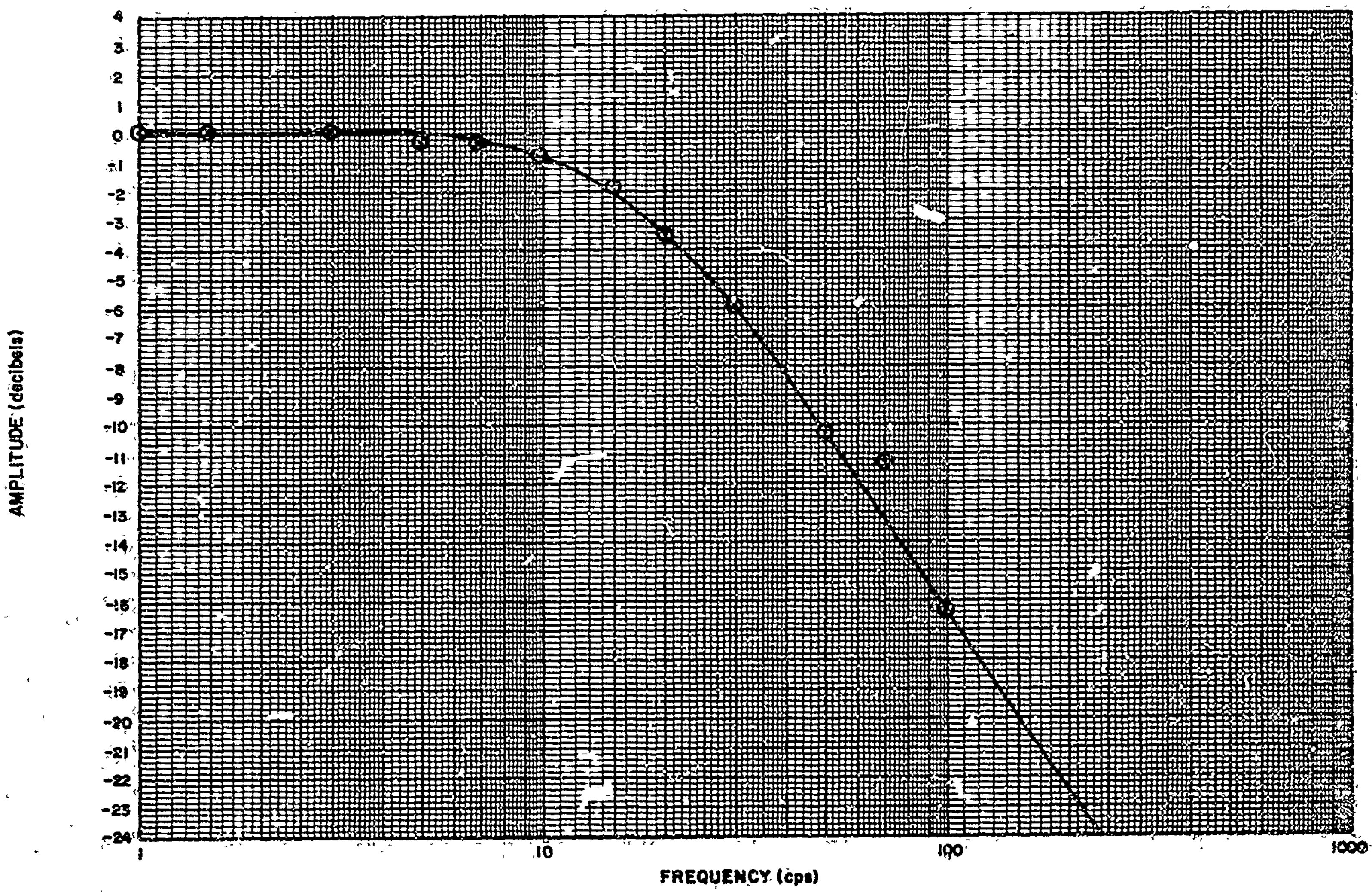


Figure 1. Angle Modulator Frequency Response

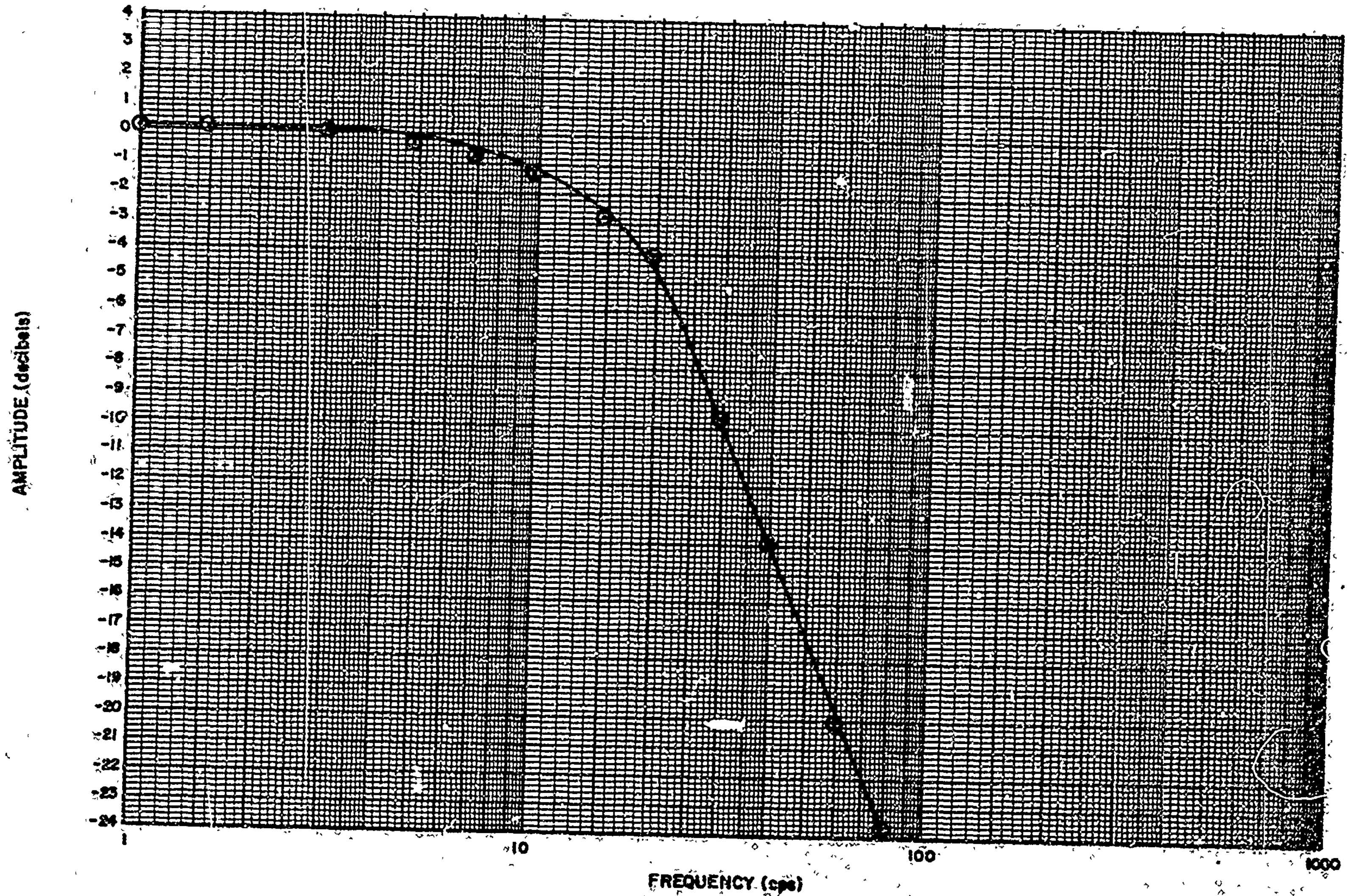


Figure 2. Combined Preamplifier and Angle Modulator Frequency Response

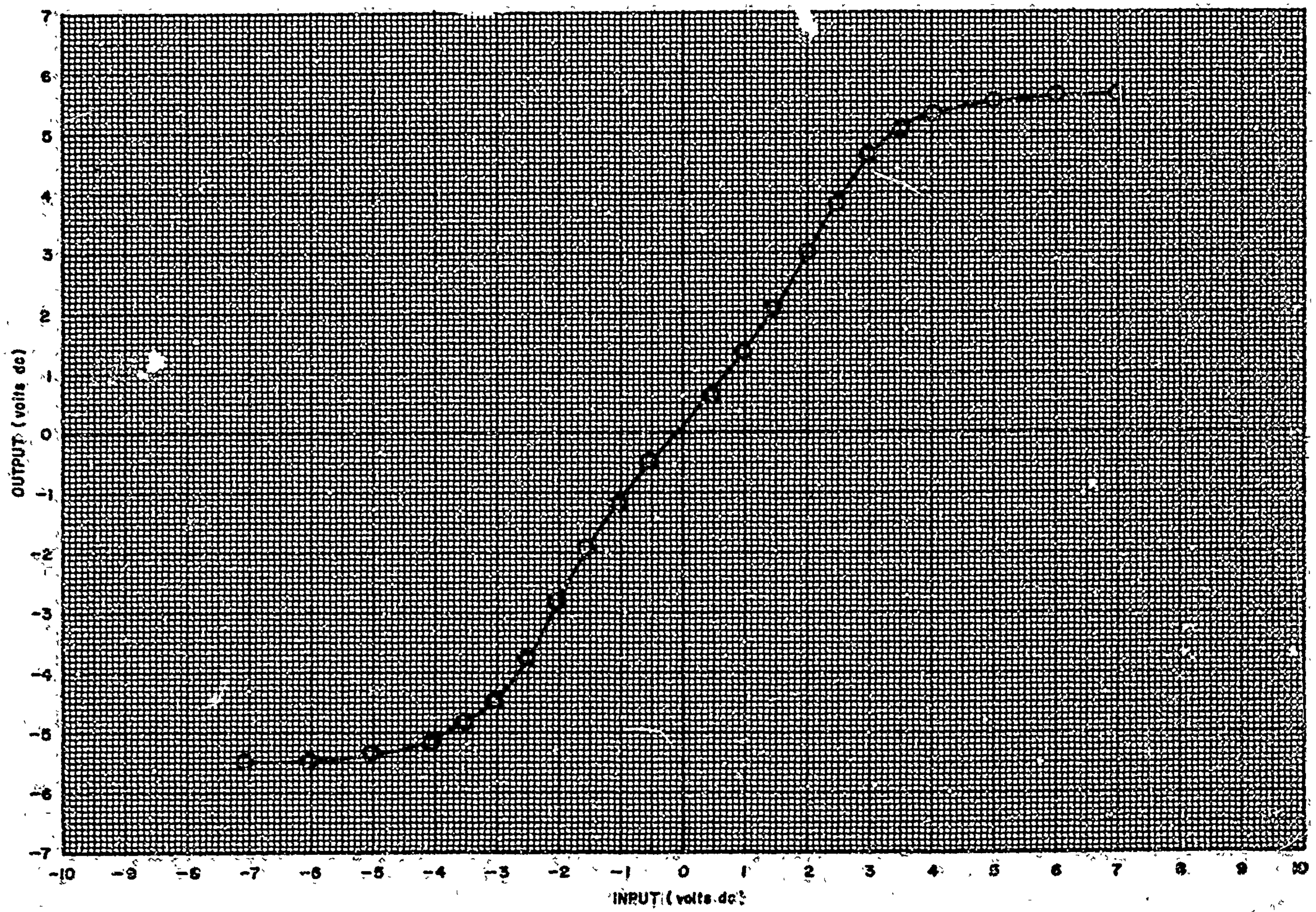


Figure 3. Angle Modulator Linearity Curve

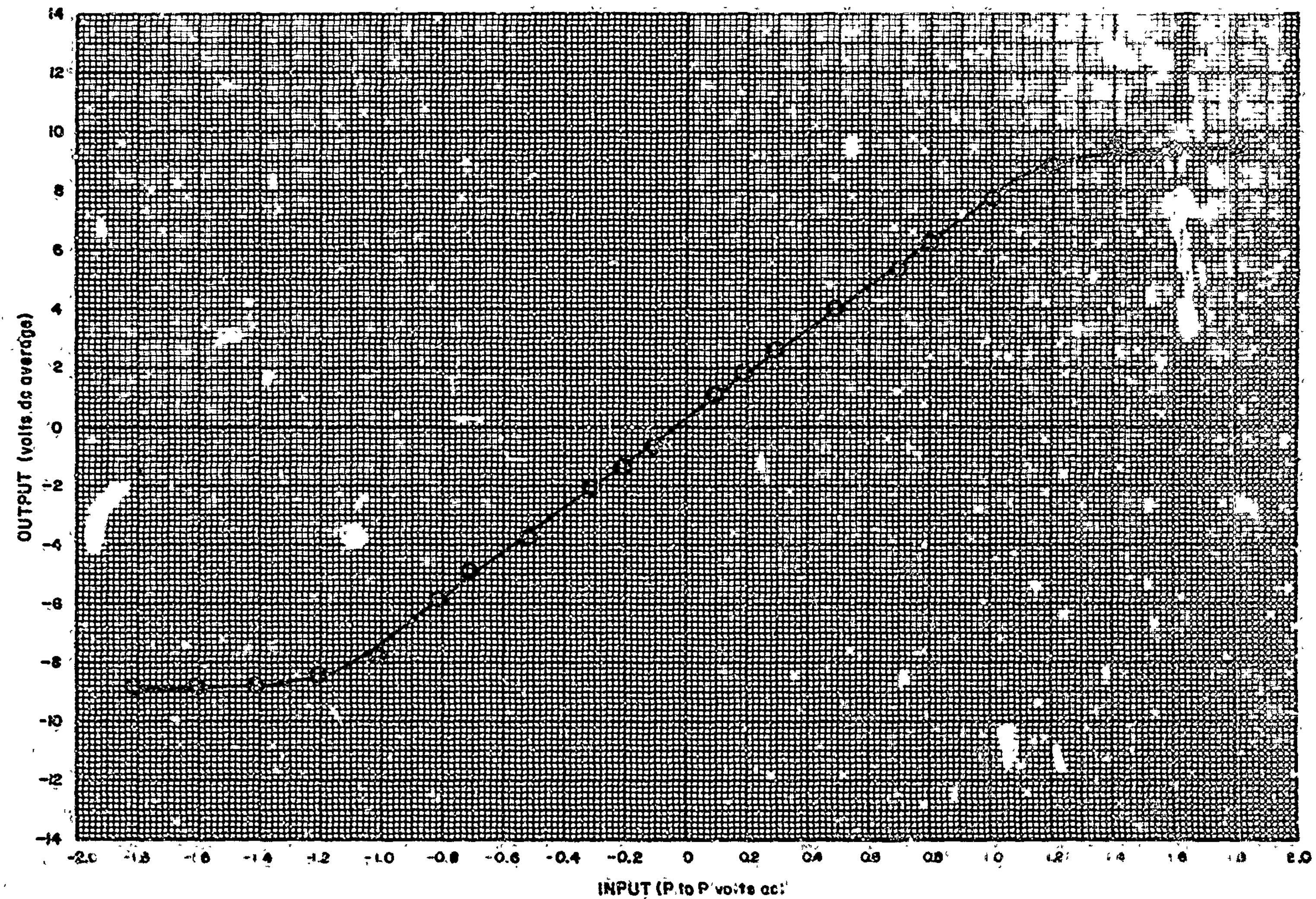


Figure 4. Preamplifier Linearity Curve

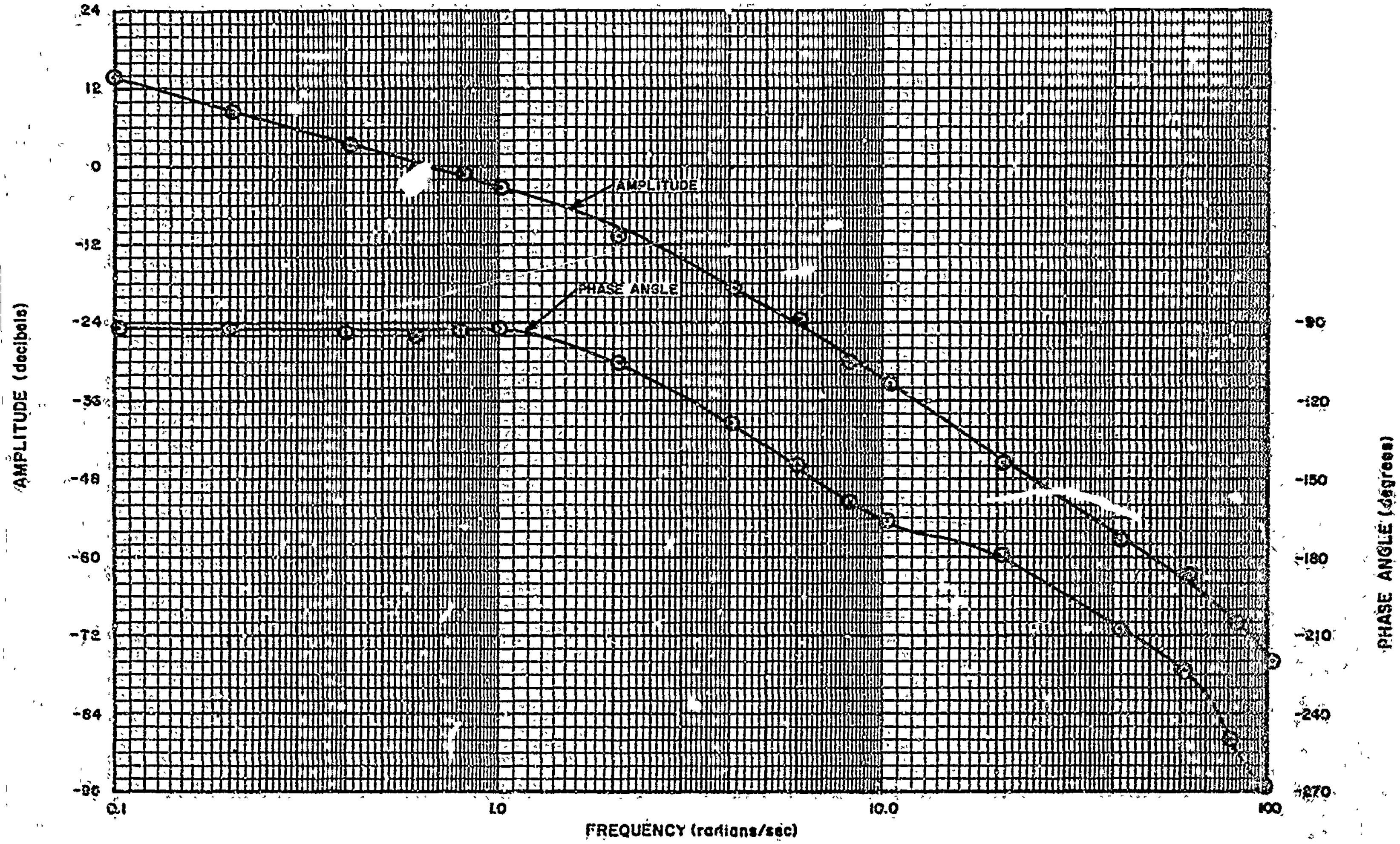


Figure 5. Actual Mount Azimuth Bode Plot

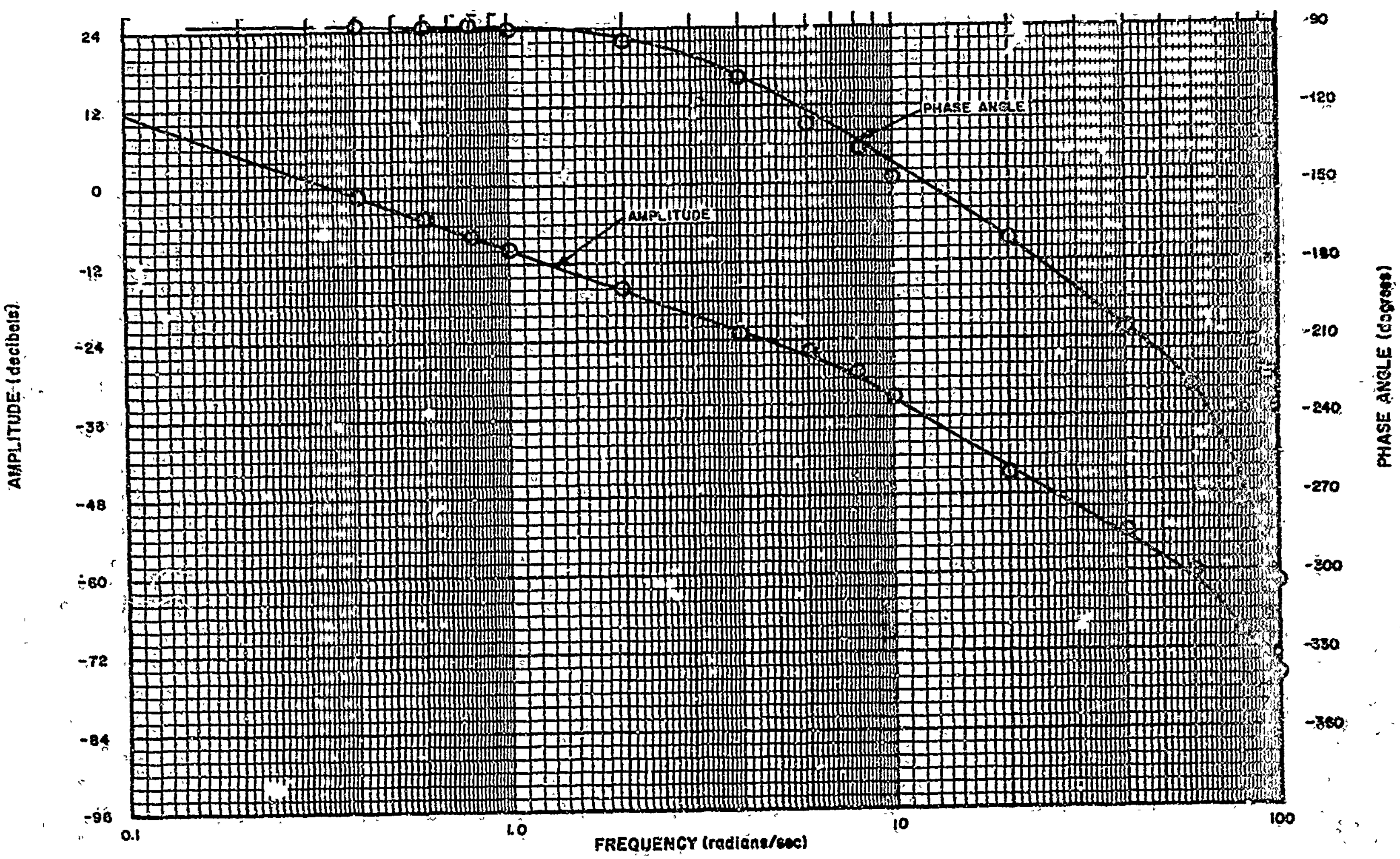


Figure 6, Actual Mount Elevation Bode Plot

comparison of the chosen transfer function step response with the mount step response is necessary before the chosen transfer function can be accepted as being accurate enough for design purposes.

To compare the two step response plots, the approximate transfer function was programmed on an nalog computer. The step response of the system simulated on the analog computer was then compared with the mount step response plotted directly from the mount. The first guess transfer functions erred more than is desirable for a good design, even though the Bode plot indicated a "good match." Using the simulation of the approximate system, a better match was obtained by varying the transfer function constants until the step response of the simulated system most nearly matched the actual mount step response. The new constants were then read from the computer and inserted into the approximate transfer function, and another Bode plot was made. This new Bode plot was found to agree closely with the actual mount Bode plot. The compared step response curves for the new matched transfer function are shown in Figures 7 and 8. Bode plots of the two are shown in Figures 9 and 10. By using both the Bode plot and the step response, a "good match" was obtained. The new transfer functions are given as:

1) Azimuth axis transfer function

$$G_{(S)} = \frac{0.66}{S\left(\frac{S}{9} + 1\right)\left(\frac{S}{22} + 1\right)}$$

2) Elevation axis transfer function

$$G_{(S)} = \frac{0.256}{S\left(\frac{S}{10} + 1\right)\left(\frac{S}{80} + 1\right)}$$

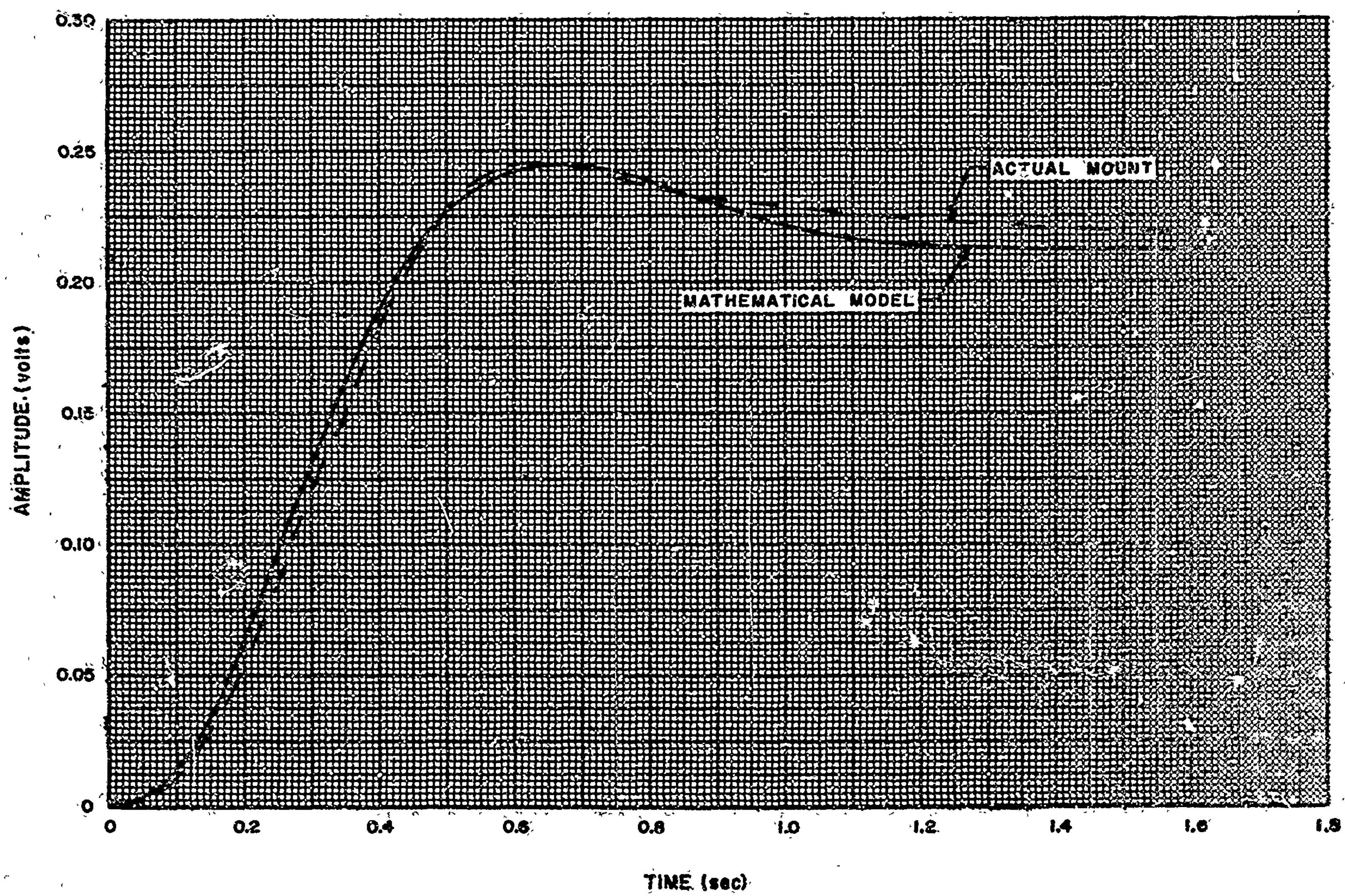


Figure 7. Azimuth Axis Step Response Comparison

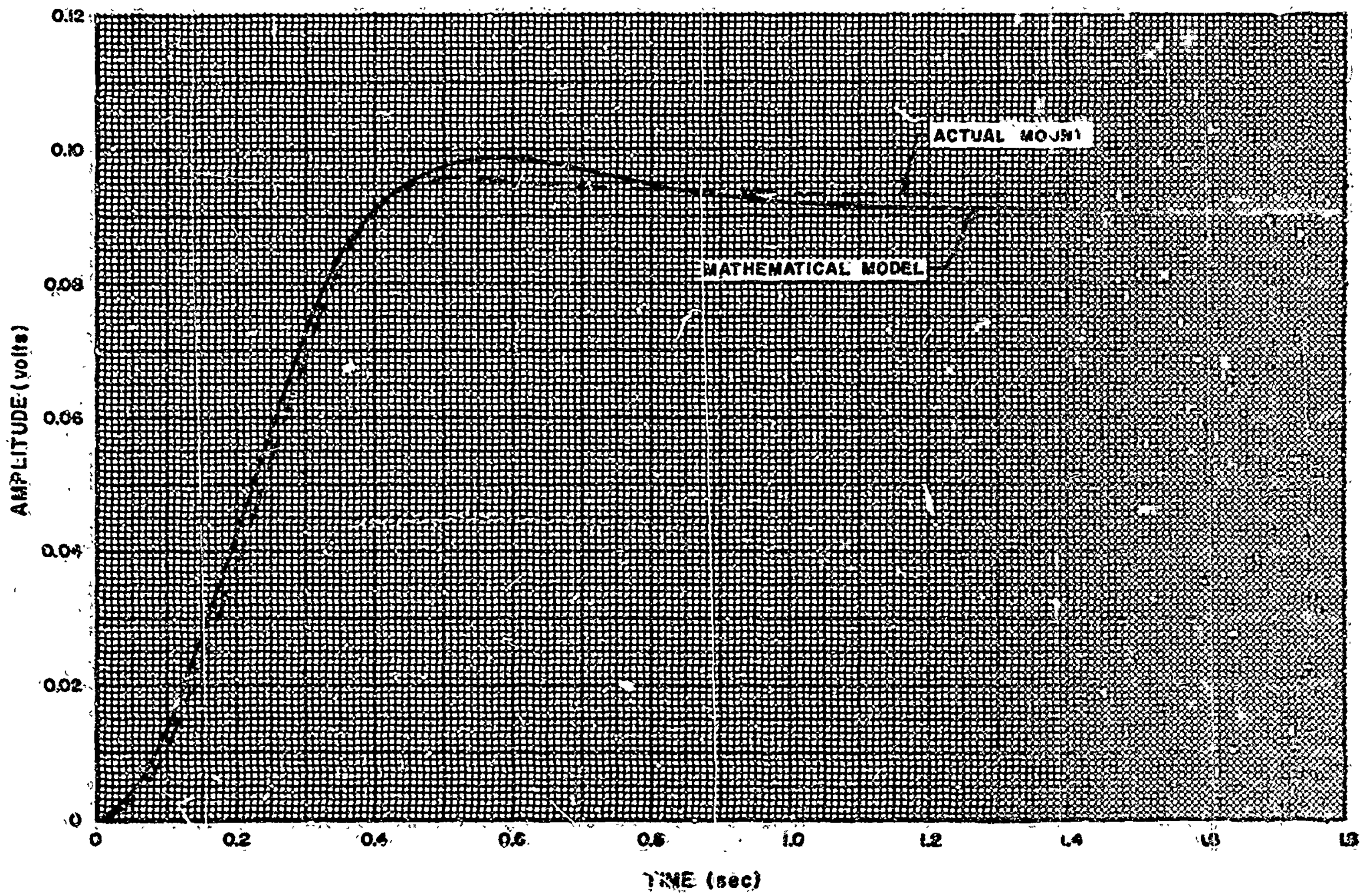


Figure 8. Elevation Axis Step Response Comparison

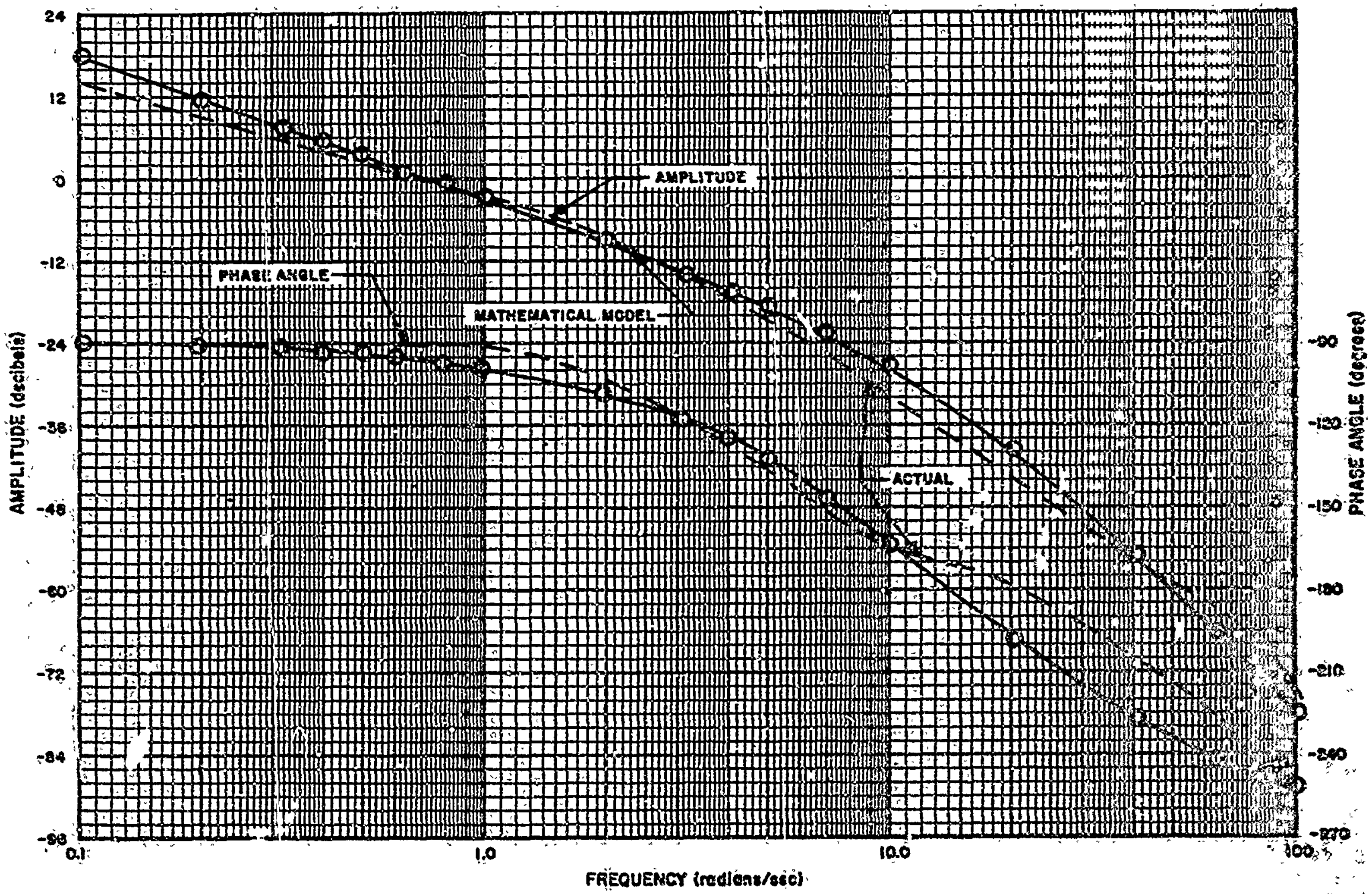


Figure 9. Azimuth Axis Bode Plot Comparison

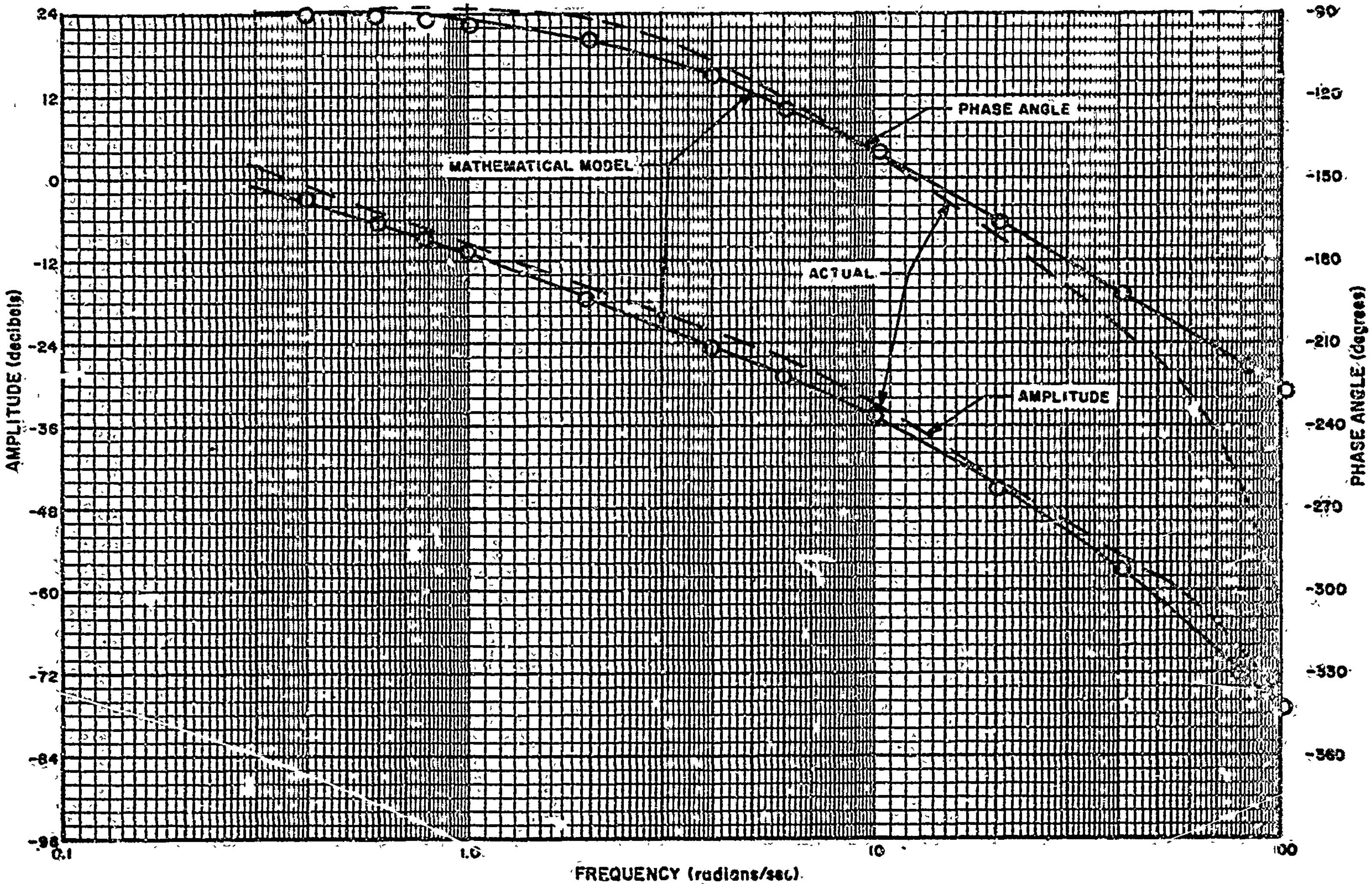


Figure 10. Elevation Axis Bode Plot Comparison

Section V. COMPENSATION DESIGN

Using the transfer functions derived above, frequency response techniques were used to design the needed compensation. In order to carry out the design properly, the following general performance specifications were assumed:

1)	Phase Margin	40 to 60 degrees
2)	Bandwidth	3 to 8 radians/sec
3)	Maximum M_p (Servo Design Parameter)	1.5

The dynamic tracking error to a unit acceleration input was not to exceed 1 milliradian. The maximum angular tracking rate was to be more than 10 degrees/sec. The last specification is contained in the bandwidth specification, but the relationship between the two specifications is vague in some cases. While maintaining an angular rate of 10 degrees/sec minimum, the bandwidth specification must be kept in mind. The bandwidth will probably limit the maximum angular rate to a value below 20 degrees/sec.

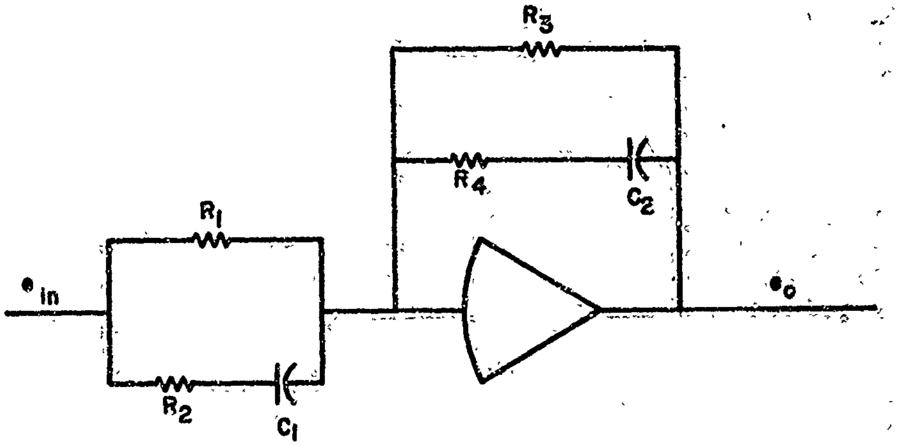
These specifications are helpful during the design stage, but the maximum error specification is the most important from a practical standpoint, since the tracking error of the mount will determine the point accuracy of the tracking system. Therefore, when testing the compensated system to determine if it will meet the specifications, it is only necessary to test the system using a worse case input and measuring the error. For other applications this might not be true, but for the need here, it is sufficient.

In addition to specifications, other considerations were noted before the final design was started. Tries were made of several types of compensation before the design discussed here was selected as the most desirable.

It was decided that active compensation would be used. With active compensation, the operational amplifier limitations must be considered. On some conventional lead or lag compensation using operation amplifiers, capacitive loading becomes a serious problem. A capacitor connected either from the output to ground or from the input to the summing junction on an operation amplifier will have a low impedance at some frequency. When a frequency is reached where the impedance is low

enough to cause excessive current to be drawn from an amplifier, oscillations will usually occur which saturate all amplifiers connected with the one which is overloaded.

Compensation, using a technique described in several handbooks, aids in eliminating this problem. The loading problem is avoided by designing the compensation networks with a resistor, in series with all capacitors. Figure 11 shows the general diagram and general equations for such a compensation network. The compensation was designed using straight line Bode plots. Parameters, necessary to compensate the system to meet the specifications, were inserted on the plots. The compensation network constants were read from the straight line plots after the theoretical compensated system was checked to ensure that the specifications had been met. The actual design involved a rough guess design, plus a trial and error final design to find a "best set" of network constants.



$$\frac{e_o}{e_{in}} = -\frac{R_3}{R_1}\left(\frac{1 + R_4 C_2 S}{1 + (R_3 + R_4) C_2 S}\right)\left(\frac{1 + (R_1 + R_2) C_1 S}{1 + R_2 C_1 S}\right)$$

$$\frac{e_o}{e_{in}} = -K\left(\frac{1 + \tau_1 S}{1 + \tau_2 S}\right)\left(\frac{1 + \tau_3 S}{1 + \tau_4 S}\right)$$

$$K = \frac{R_3}{R_1}, \quad \tau_1 = R_4 C_2, \quad \tau_2 = (R_3 + R_4) C_2$$

$$\tau_3 = (R_1 + R_2) C_1, \quad \tau_4 = R_2 C_1$$

Figure 11. General Form of Compensation Network

The system design was carried out using the error which was based on a unit acceleration input, because this input simulated the actual input as closely as was practical using standard inputs. Assuming that the mount position potentiometers are linear, and that the effect of the load on the potentiometer is negligible, the 1-milliradian maximum tracking error may be related to the error coefficients of the system, as discussed in the following paragraphs.

If a potentiometer supply voltage of ±10 volts dc is assumed, then for 360 degrees of angular travel, the degrees of volts ratio would be 18 degrees/volt. This is approximately 0.3 milliradian/millivolt. In this particular case, a 2-millivolt (approximately 0.6 milliradian) maximum error was chosen for simplicity. To achieve this tracking error for a unit acceleration input, a zero error for a unit velocity input is needed. Otherwise, the loop gain requirement would be high enough to make compensation nearly impossible. The basic, uncompensated, system has only one pole at the origin. To design a system with zero error to a unit velocity input, two poles at the origin are necessary. Therefore, an integrator must be added to the control loop before the design is continued. With the integrator added, a finite error will exist for a unit acceleration input. This finite error is related to the acceleration coefficient by:

$$\frac{1}{Ka} = 0.002 \text{ volt (for this case) if the system has unity feedback.}$$

For the particular case under consideration here, the acceleration coefficient (Ka) was found to be 500 for a maximum tracking error of 0.6 milliradian.

The actual design for the azimuth axis gave a convenient value for the acceleration coefficient of Ka = 440. For this value of Ka, the theoretical maximum tracking error is 0.0023 volt. When this is converted to an equivalent angle, the maximum error is 0.7 milliradian.

The predicted performance for the compensated azimuth axis is given by the following values:

1) Phase Margin - 50 degrees
2) Bandwidth - 4.5 radians/sec
3) Mp - 1.4

The azimuth axis compensation network transfer function is:

$$G_{(S)} = \frac{660\left(\frac{S}{0.1}+1\right)^2\left(\frac{S}{10}+1\right)\left(\frac{S}{1}+1\right)}{S\left(\frac{S}{0.01}+1\right)^2\left(\frac{S}{44}+1\right)\left(\frac{S}{100}+1\right)}$$

Compensation of the elevation axis was found to be relatively simple since the same compensation network gave the desired results with only an addition of loop gain. The predicted performance for the compensated elevation axis is given by the following values:

1) Phase Margin 65 degrees
2) Bandwidth 6 radians/sec
3) M_p 1.2

The transfer function for the elevation axis compensation network is:

$$G_{(S)} = \frac{1540\left(\frac{S}{0.1}+1\right)^2\left(\frac{S}{10}+1\right)\left(\frac{S}{1}+1\right)}{S\left(\frac{S}{0.01}+1\right)^2\left(\frac{S}{44}+1\right)\left(\frac{S}{100}+1\right)}$$

Transfer functions for the complete compensated system are as follows:

1) Azimuth axis

$$G_{(S)} = \frac{440\left(\frac{S}{0.1}+1\right)^2\left(\frac{S}{10}+1\right)\left(\frac{S}{1}+1\right)}{S^2\left(\frac{S}{9}+1\right)\left(\frac{S}{22}+1\right)\left(\frac{S}{0.01}+1\right)^2\left(\frac{S}{44}+1\right)\left(\frac{S}{100}+1\right)}$$

2) Elevation axis

$$G_{(S)} = \frac{400\left(\frac{S}{0.1}+1\right)^2\left(\frac{S}{10}+1\right)\left(\frac{S}{1}+1\right)}{S^2\left(\frac{S}{10}+1\right)\left(\frac{S}{80}+1\right)\left(\frac{S}{0.01}+1\right)^2\left(\frac{S}{44}+1\right)\left(\frac{S}{100}+1\right)}$$

A block diagram for the complete compensated system is shown in Figure 12.

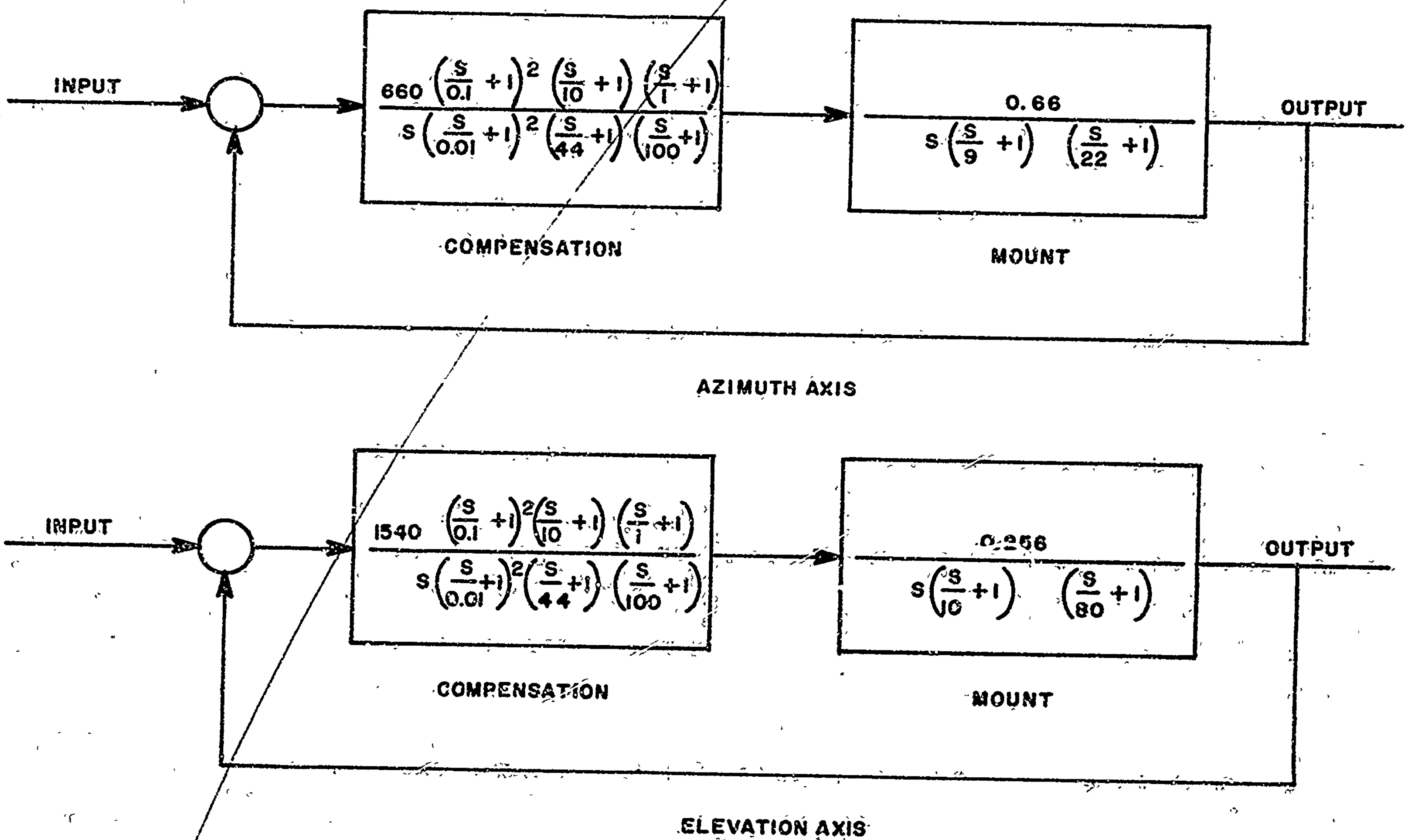


Figure 12. Compensated System Block Diagram

Section VI. CONTROL CIRCUIT OPERATION

This discussion includes a description of the actual control circuits and their operation. The control circuits include the compensation circuit, as well as circuits for mode control, safety, and power.

The primary power for the relay control circuits is 28 volts dc. Other external power required includes 12 volts rms, 400 cps, 115 volts ac, 60 cps. All other power is obtained from self-contained power supplies.

In Figure 13 the mode control logic, along with parts of the safety circuitry, is shown. When power is applied to the relay logic circuits, all relay coils, except K5, are left in the thede-energized state until the mode push button is pressed. By connecting power directly through contact K3/3 to the coil of K5, the system will always be in the manual mode when power is first applied or, anytime, when K3 is deenergized. Relay K3 is energized only when the system is in the automatic mode.

The notation 2K0 means that two K0 relays are used to provide the necessary number of contacts. To place the system in the automatic mode, the push button control, either local or remote, is pushed. The push button energizes relay K0. Contacts on K0 activate the coils of K7, KA, and K3. Power also is connected to the automatic light on the remote panel. Relays K7, KA, and K3, as well as the automatic light, are locked in through K3/1 and K5/1. The logic circuitry is now in the automatic mode. When the push button is released, the system remains in the automatic mode, but relay K4 is energized through K0/3, K3/2 and K5/2. Relay K4 is locked in through contacts K4/2, and K6/2. To return to the manual mode, the push button is again pushed. Contact K0/2 energizes relays K5 through K4/3. Relay K5 along with the manual light is locked on through K3/3 which was closed when K5 was energized. When K5 picked up, it also deenergized the automatic light and the coils of KA and K7. As the button is released again, K6 is energized through K0/2, KUL/2 and K5/3. Relay K6 locks in through K6/1 and K3/1. Energizing K6 releases K4, and the system is ready to start another cycle. Relays K7, KA, and K3 are the automatic track relays. Relay K5 is the manual track relay. Contacts from K7, KA, and K3 are used to shift the tracking circuits from the manual mode to the automatic mode and back to the manual mode.

In Figure 14 the control circuit for the elevation axis is shown. In the manual mode, K7/3 into amplifier one is closed. This connects the stick elevation output through the elevation gain potentiometer to the

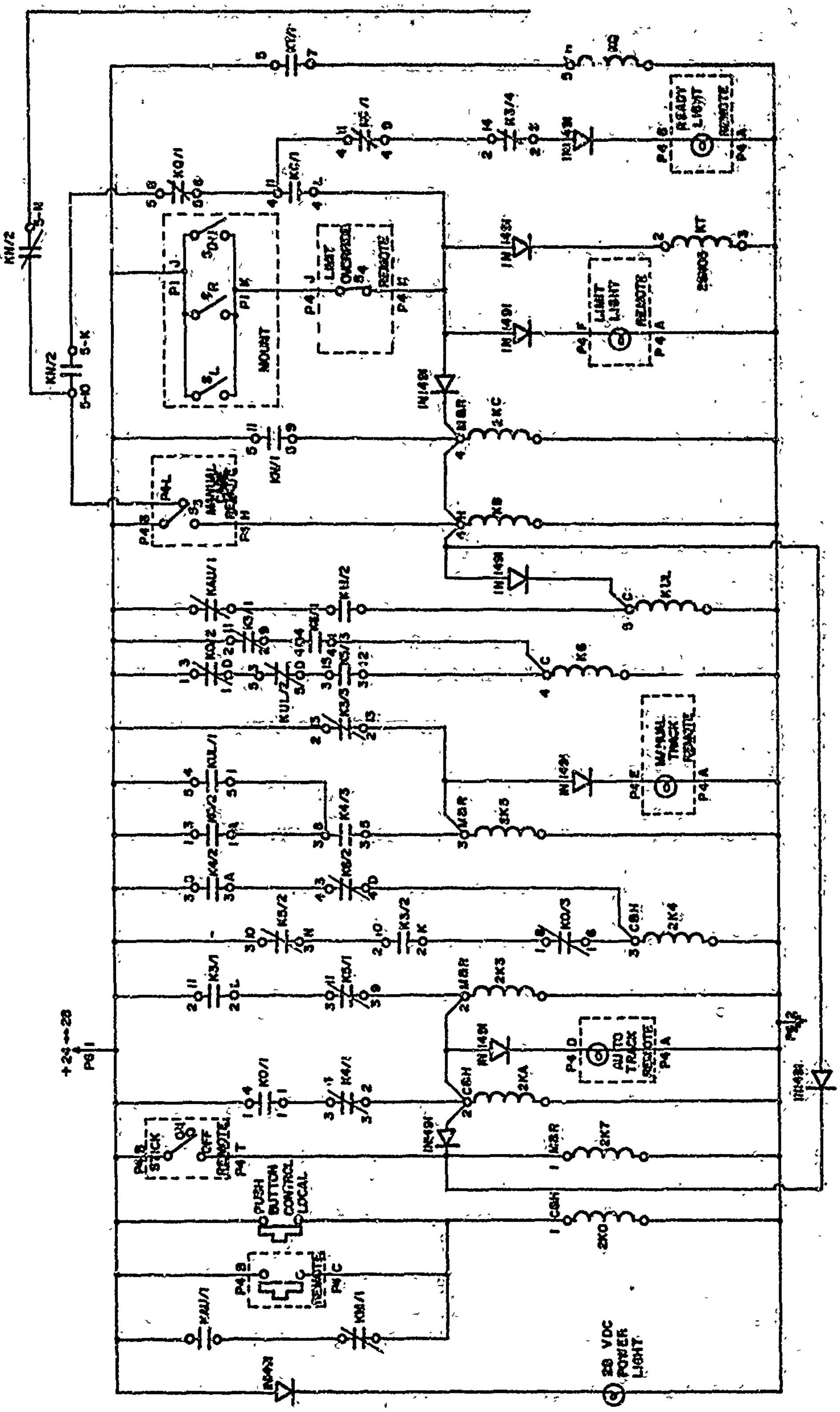


Figure 13. Mode Control Logic

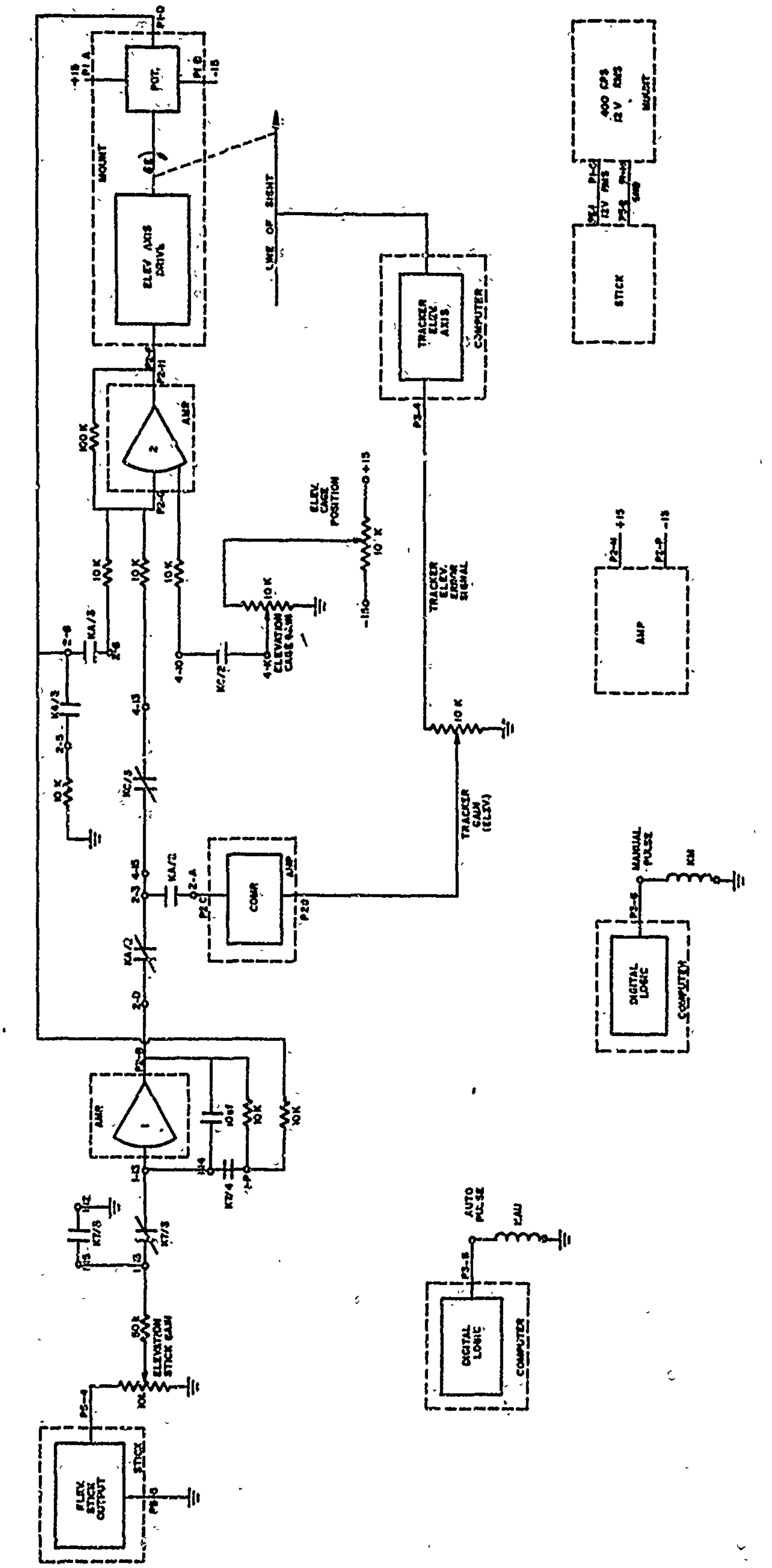


Figure 14. Elevation Axis Control Circuit

integrator circuit around amplifier one. The position signal from the stick is converted to a rate signal by the integration. Contacts KA/2 and KC/3 connect the rate signal to the input of amplifier two. The output of amplifier two is used to drive the elevation axis of the mount. A potentiometer pickoff furnishes mount position information to amplifier two through KA/3. When the system is switched to the automatic mode, the stick is disconnected from the integrator and connected to ground by K7/3. The integrator is switched to accept an initial condition by K7/4. This operation allows the mount position to be stored at the output of the integrator whenever the system is in either the automatic or the cage mode. By storing this information, a smooth switch may be made back to the manual mode at anytime. Contact KA/2 connects the tracker output in place of the integrator output, and KA/3 disconnects the potentiometer from amplifier two and ties it through a 10K resistor to ground.

The azimuth axis operation is the same, except for the slow return network, consisting of KC/4 and the TI-622 diodes. This network will be discussed as part of the caging circuit.

Relay KAU is a sensitive relay to be operated by the digital logic circuitry. When the digital logic determines that conditions have been met for a successful automatic track, relay KAU is turned on for about 200 milliseconds and then off. Contact KAU/1 closes the push button circuit through KM/1, and the system is placed in the automatic mode. When the digital logic determines that conditions are no longer favorable for the automatic track, relay KM is turned on for about 200 milliseconds and then off. This closes KM/2 while opening KM/1. With KAU/1 and KM/2 closed, KUL is picked up, and K5 is energized through K4/3. Thus, the system is placed in the manual mode in a sequence similar to push button operation.

To manually cage the mount, the manual cage switch is operated, energizing relays KC, KB, and K7. The azimuth control circuit is shown in Figure 15. With relays KC, KB, KUL, and K7 picked up, the azimuth integrator is switched to accept an initial condition from the mount azimuth position potentiometer, as described earlier. Contact KB/1 disconnects the normal input from amplifier four. At the same time, KB/2 connects a preset cage voltage to amplifier four input. The mount proceeds to null out to the preset cage position. Once the desired cage position is reached, the system may be switched back to manual operation. A signal is applied to KUL whenever the system is caged; therefore, when the caging operation is complete, the system will always be in the manual mode. Manual caging occurs in the same sequence for both axes, except for the operation of the slow return network, mentioned earlier. Due to the high mass and large angle of travel of the

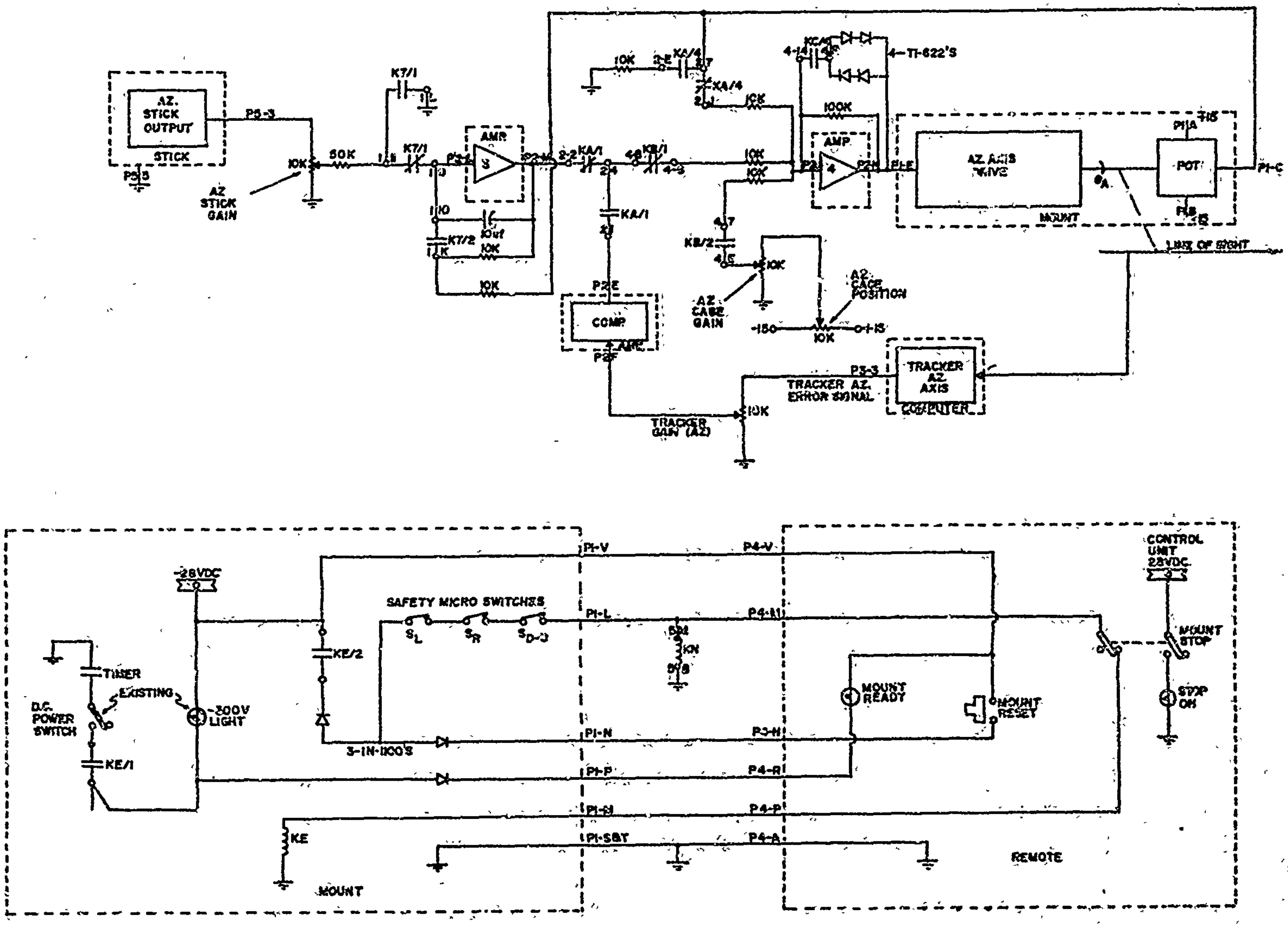


Figure 15. Azimuth Axis Control Circuit

azimuth axis, it is undesirable to allow this axis to cage at a high angular rate. To prevent this high rate, the TI-622 diodes are connected back-to-back across amplifier four, whenever the system is caging.

Two sets of microswitches are used to activate the safety circuits. As shown in Figure 13, the first set of switches connects 28 volts dc to the limit override switch on the remote panel. If either of the first set of microswitches is closed while the limit override switch is closed, relays KT, KC, KB, KUL, and K7, along with the limit light, are energized. Then, the system starts an automatic cage sequence and continues the sequence until KT times out. At this time, KT picks up relay KQ, and the system automatically returns to the manual mode. It is not necessary for the microswitches to remain closed throughout the sequence, since the cage system is locked in through KQ/1 and KC/1. When the sequence is completed and KQ/1, and K3/4 are closed, the ready light will appear, indicating that the system is now finished caging. It is in the manual mode, and KQ is again deenergized.

A second set of microswitches is shown in Figure 15. If the microswitches are all closed, the mount reset button may be pressed to pick up relay KE through the mount stop switch. When the mount reset button is released, relay KE will remain energized through KE/2 if the mount 28 volts dc is on. With KE energized, the dc power switch may be closed to place the mount in a ready condition. Both the mount ready light on the remote panel and the dc power light on the mount indicate the ready condition when all necessary operations have been performed. When any part of this circuit fails, the dc power is removed from the mount while the excitation and the high performance amplifier are left energized. The excitation and the power amplifier provide breaking action when the dc power is removed. An emergency stop is provided for manual operation on the remote panel by the mount stop switch. Relay KN applies a cage signal whenever this stop circuit indicates trouble.

A diagram of the compensation network for both axes is shown in Figure 16. As noted earlier, the same network was used for the elevation axis, except that the gain was increased to the value shown in the compensated system transfer function, included in Section V.

Zener diodes were used on all operational amplifiers to prevent amplifier overload. Any of several types may be used, provided that the ones chosen limit the voltage to 8 to 10 volts. Although these diodes are not shown on the diagrams included in this report, they were installed back-to-back across the feedback network of the operational amplifiers.

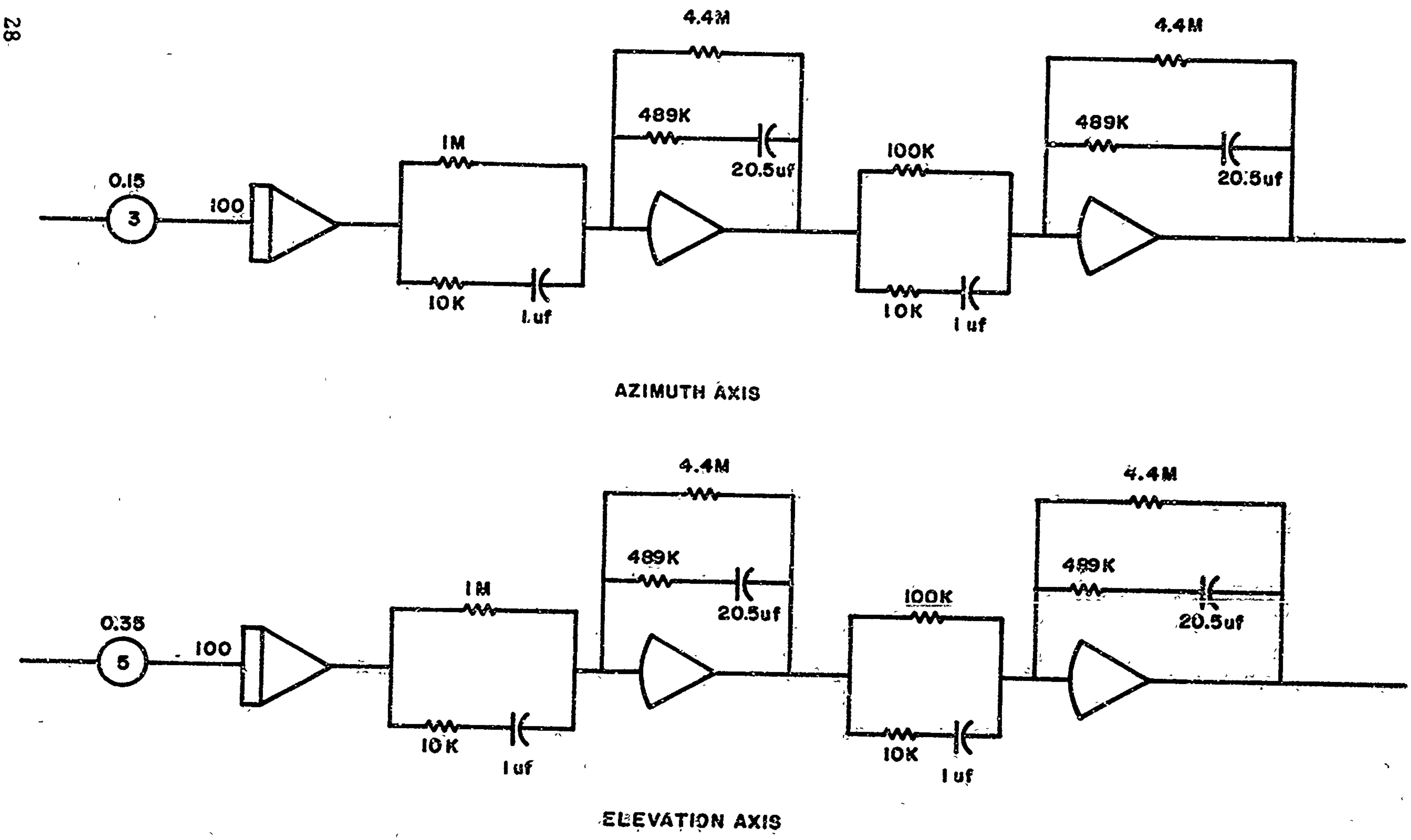


Figure 16. Compensation Network Diagram

Section VII. SYSTEM TESTS

The compensated system was tested, using the setup shown in Figure 17. A worse case fly-by was provided by the cover follower as an input. One axis was tested at a time. Figure 18 shows the angular velocity plot and the error in angular position as a function of time, resulting from a simulated worse case fly-by for the azimuth axis. A simulated angular position fly-by was used on the elevation axis. The angular position and the resultant angular position error as a function of time are shown in Figure 19. A brief test was conducted to determine the effect of dither on the tracking error of both axes. The dither signal was put into the system as an input to amplifiers nine and eighteen, as shown in Figure 17.

Another test was conducted to establish the maximum gain that could be used without designing new compensation networks. This test included changing the setting on potentiometers three and five (Figure 17). The tracking error was checked for increased gains, and a discussion of the results is contained in Section VIII.

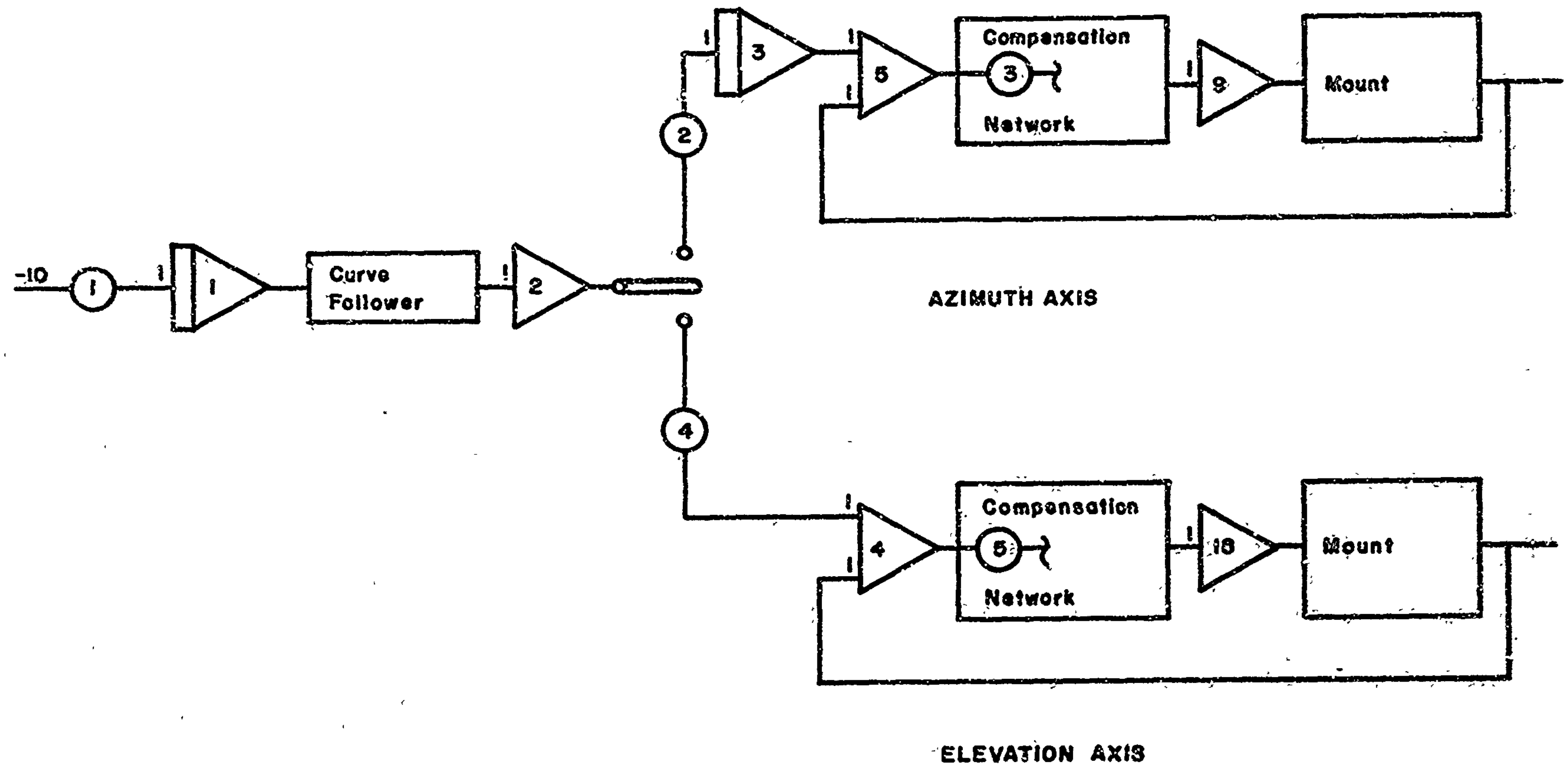


Figure 17. System Test Diagram

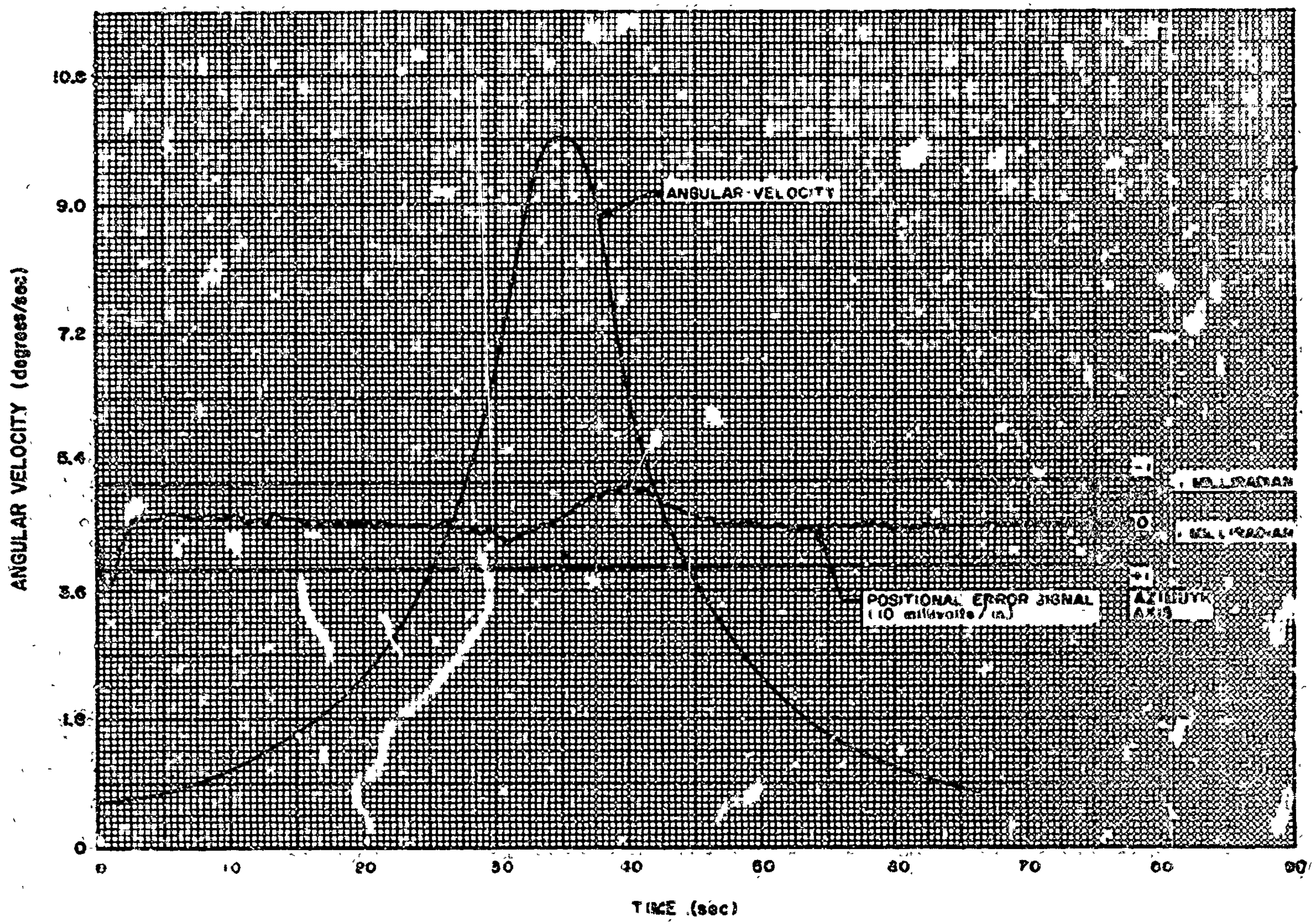


Figure 18 Azimuth Axis Angular Velocity and Positional Error Plots

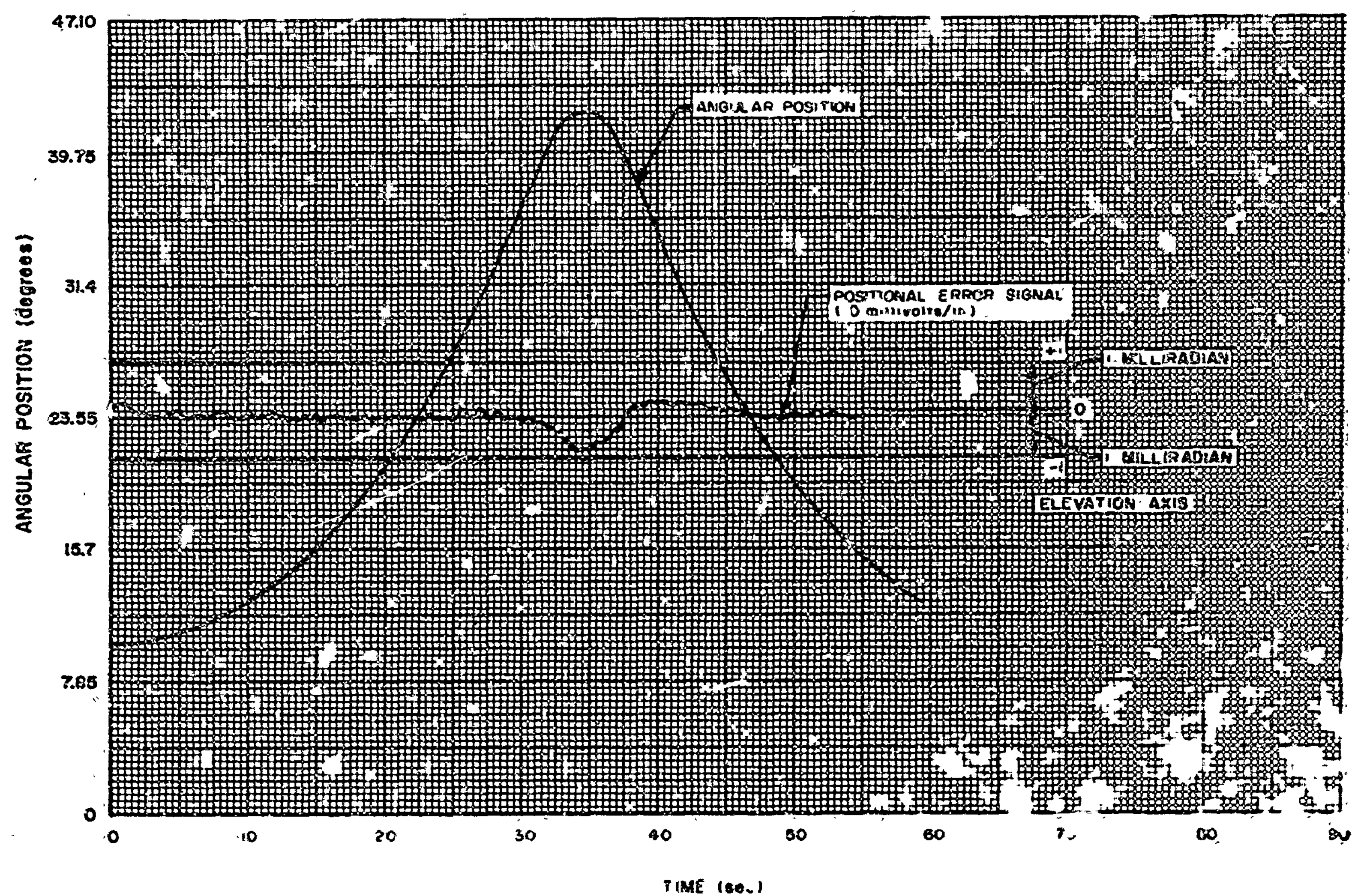


Figure 19. Elevation Axis Angular Position and Positional Error Plot

Section VIII. RESULTS AND CONCLUSIONS

The NIKE-AJAX mount can be modified to track to less than 1-milliradian error, using an input such as the fly-by. If the mount is not in excellent operating condition, valuable time can be wasted in trying to obtain a mathematical model of the system. Figure 18 shows that a maximum tracking error of 0.9 of a milliradian can be expected for the azimuth axis. Figure 19 indicates that the elevation axis' maximum tracking error is similar to the azimuth axis' error.

Dither did not improve the performance noticeably for either axis. If smaller tracking errors were required, then dither might become necessary.

An increase in the loop gain does increase the tracking accuracy. However, the system has a high frequency oscillation which occurs when the loop gain is increased much above 500. This is probably due to a resonant peak which is normally well below the 0-decibel line but, as the loop gain is increased, the peak rises and, at some value of gain, actually goes above the 0-decibel line.

If time is available in the future, further testing could be conducted to determine the actual system specification. However, the system performs well enough with the present compensation to produce the required accuracies for the present program, and no further tests are necessary at this time.

The compensation design discussed here was for the mount alone. If other system dynamics are introduced by an automatic tracking loop, then this design will not yield the same results. For such cases, a new compensation network design would probably be required.

Appendix

MOUNT PREPARATION

If the mount must travel through an angle of approximately 360 degrees, the various geared potentiometer outputs are of little value. These gears were found to have backlash which also made their use undesirable. Direct coupled potentiometers were used to help minimize the system nonlinearities. The old synchros were not needed, and so they were removed.

One point worth further discussion concerning the direct coupled potentiometer involves the azimuth mechanical design. If a potentiometer is connected to the bottom of the slipring cylinder, without first checking the cylinder mechanical mounting, several degrees of backlash may result. The cylinder was required to follow the mount in the original NIKE-AJAX system, but only roughly. A potentiometer may be mounted directly to the elevation axis without backlash problems. However, the elevation axis was stiff on the mount used for this program because of plastic bearings used on this axis. It was necessary to add an adjustable voltage of 400 cps (of proper phase) to the preamplifier input to obtain a proper balance. To reduce the noise in the mount electronics, all unused inputs to the angle modulator were removed.

It is important that the large, resistor capacitor time constants of the angle modulator input networks are checked, to determine if the long time constants will interfere with the desired bandwidth specification. In the particular case discussed here, all of the capacitors were removed, and a smaller value capacitor was inserted in order to reduce the noise content of the output.

To prevent operation of the preamplifiers in their nonlinear region, potentiometers were installed between the angle modulator output and the preamplifier input.

Jacks were installed on the angle modulator and preamplifier chassis to allow observation of signals necessary for proper system adjustment.

The filament circuits were wired for two voltages on units which otherwise were interchangeable. These were rewired for the same voltage for both channels.

The selenium rectifiers used in the 28 volts dc power supply malfunctioned and were replaced by silicon diodes.

Many of the relay circuits were intermittent. The 30-second timer in the relay control circuit had a bad microswitch. These problems were corrected.

It was necessary to completely clean and to lubricate the azimuth axis' track and rollers. The elevation axis' plastic bearings were cleaned and lubricated.

Care must be exercised at all times not to overdrive any part of the system. With all of the nonlinear problems minimized, the practical system will still contain enough nonlinear properties so that careful design must be maintained.

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13. ABSTRACT

A procedure followed in modifying a NIKE-AJAX mount for use with an optical tracking system is presented in this report. Some aspects of the required cleanup and servicing procedure are covered, and a discussion of the complete control system design is included. Tracking errors, resulting from the servo design and mount nonlinearities, are discussed both in reference to the design, as well as in reference to the results of actual tests. An attempt has been made to keep the discussion as general as possible in order to allow maximum future use of the information obtained from this modification.

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